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BUILDING NEW TEMPERATURE INDICES FOR A LOCAL UNDERSTANDING OF GRAPEVINE PHYSIOLOGY

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Abstract

Aim: Temperature corresponds to one of the main terroir factors influencing grapevine physiology, primarily evidenced by its impact on phenology. Numerous studies have aimed at expressing time with thermal indices such as growing degree days (GDD) and have thus enabled a better modelling of grapevine responses to temperature. However, some works have highlighted the need to adapt GDD to the considered pedo-climatic context and grape variety or to refine the time step at which temperature variables are computed. The present study aims to investigate the hypothesis that grapevine response to temperature depends on the production context, *ie.* plant material, pedo-climate, topography, orientation and cultural practices, and that thermal indices should then be locally adapted.

Methods and Results: GDD with different base temperatures but also other indices based on other algebraic equations on daily average temperature were calculated starting from the bud break date and using data from weather stations located in the Bordeaux region (France), California (USA) and Israel. The dates of flowering and veraison were expressed according to each of these indices for three commercial blocks located near each weather station. For each block, the relative differences in the flowering and veraison dates were calculated for any couple of years and summed squared. The number of studied years considered ranged from fifteen to five depending on the blocks. The relative difference between two dates was computed as their difference in index-related degrees divided by the average index-related amount of degrees to reach veraison. The thermal index which minimizes the sum of the relative differences of flowering and veraison dates for all the years of the same block is considered to best illustrate the temperature local effect. As such, this local effect includes both grapevine physiological response to temperature and the difference between the weather station data and the conditions actually experienced by the vines.
Dates of flowering and veraison of all years coincide when expressed in a given thermal index for most of the blocks. The hypothesis whereby temperature is a predominant factor in grapevine phenology may thus be confirmed. Moreover, the thermal indices allowing such an adjustment are different between blocks of different locations, thus demonstrating that temperature effects on grapevine phenology are better captured when considered according to locally calibrated indices.

Conclusion: Temperature effects may be better captured by different thermal indices depending on the local context.

Significance and Impact of the Study: In a precision viticulture context, a growing access to local and higher resolution weather data and grapevine observations enables models to be used locally. The present study therefore corresponds to a first attempt to highlight the importance of calibrating a local thermal index to improve the performance and operational relevance of any temperature-based model.

Keywords: Local thermal index, precision viticulture, terroir factors

Introduction

Temperature corresponds to one of the main terroir factors influencing grapevine physiology, primarily evidenced by its impact on phenology (Tonietto and Carbonneau, 2004; Pagay and Collins, 2017; Prats-Llinàs *et al.,* 2020). Many models have thus shown the importance of considering a temperature-based timeline, called thermal indice in this paper, to better represent grapevine phenology (Sadras and Moran, 2013; Cola *et al.,* 2014; Leolini *et al.,* 2020; Prats-Llinàs *et al.,* 2020). This thermal index is then used to express the timing of any variable aimed at explaining grapevine development (Suter *et al.,* 2019; Parker *et al.,* 2020). However, some studies have shown the interest of parameterizing the computation of thermal indices according to the variety (Zapata *et al.,* 2015, 2017) or to the site characteristics such as topography, elevation or orientation (Neethling *et al.,* 2019; Verdugo-Vásquez *et al.,* 2020; de Rességuier *et al.,* 2020). Thus, when the objective is not to compare varieties or management methods in terms of heat requirement (Molitor *et al.,* 2020) but to use the most relevant timeline to study grapevine development, it seems interesting to locally calibrate a thermal index. The calibration of such a local index is of real operational interest for commercial vineyards, since it would allow them to better understand the site-specific performance of their vines when research work is often based on experiments in very different environmental conditions that cannot be applied for them. In order to do this, calibration of the thermal index must be possible from operational data, which are commonly available in commercial vineyards. In this paper, two types of operational data were therefore considered for the calibration of a local thermal index: weather data and the dates of achievement of the three most observed phenological stages, *i.e.* bud break, bloom and veraison.

The working hypothesis of this study is that there exists a thermal index that allows the best expression of the thermal determinism of grapevine phenology. The dates of achievement of the different phenological stages expressed in this index would therefore be consistent over the years since resulting from the same temperature-driven process. The objective of the study is to identify the thermal index that allows the best matching of the dates of achievement of the phenological stages for a given vineyard and to test whether this index is the same from one vineyard to another.

Data from three different commercial vineyards respectively situated in the Napa Valley (California, USA), Israel and the Bordeaux region (France) have therefore been analysed to support the work presented in this paper. As these vineyards are located at different latitudes, the study also tested the impact of introducing photoperiod in the thermal index as a duration of exposure to effective growing temperatures.

Material and Methods

Data Description

Data was collected from three commercial vineyards situated in the Napa Valley (California, USA), Israel and the Bordeaux region (France). They are respectively noted vineyard A, B and C in this paper. For each vineyard, three blocks planted with Cabernet Sauvignon have been studied. The three vineyards differ according to their pedo-climatic, topographic and altimetric environment, exposure as well as management strategies in terms of harvest yield and quality. As a result, the choice of plant material and cultural practices differ between vineyards, as an illustration of adaptation to local *i.e.* site-specific environmental and operational contexts. Some of these differences are summarized in Table 1.

Table 1: Characteristics of the three blocks of vineyards A, B and C.

	Vineyard A	Vineyard B	Vineyard C
Area per block (hectares)	0.5 to 2	1.2	1.1 to 1.4
Date of plantation	1994	2005 to 2011	1985 or 1986
Theoric density	2220	2500	8700
Rootstock	1103 P or 110 R	101-14 MGt or none	101-14 MGt or 3309 C

Data of vineyards A, B and C were available respectively from 2008 to 2017 (ten seasons), from to 2015 to 2019 (five seasons) and from 2001 to 2015 (fifteen seasons). For each vineyard, daily average temperatures have been recorded using a commercial weather station located within the vineyard. For each block, the dates of bud break, bloom and veraison have been collected according to the Gregorian calendar at 50% of achievement.

Computation of Thermal Indices

For each block and each year, three types of thermal indices have been calculated from the date of bud break. They are respectively noted 1, 2 and 3. Index 1 corresponds to cumulation of daily average temperature above a given base temperature and weighted by photoperiod (Index 1b) or not (Index 1a). Base temperatures from 0 to 25°C have been tested. Index 2 corresponds to cumulation of daily average temperature between a minimum and a maximum threshold temperature and weighted by photoperiod (Index 2b) or not (Index 2a). Minimum and maximum thresholds have respectively been tested from -5°C to 10°C and from 10°C to 30°C. Index 3 corresponds to cumulation of daily average temperature if situated between a minimum and a maximum threshold temperature and to a subtraction of the difference of daily average temperature with one of the thresholds if it is exceeded. The corresponding growing degrees were weighted by photoperiod (Index 3b) or not (Index 3a). Minimum and maximum thresholds have respectively been tested from -5°C to 10°C and from 10°C to 30°C. The six indices tested in the study are summarized in Table 2.

Table 2: Equations and parameters for the computation of Indices 1a, 1b, 2a, 2b, 3a and 3c.
GDD_i: growing degree days of day i, i going from the bud break date to the veraison date, T_a: daily average temperature, T_b: base temperature, T_1: minimum temperature threshold, T_2: maximum temperature threshold, P: photoperiod.

	Index 1		Index 2		Index 3	
	1a	1b	2a	2b	3a	3b
Equation	*if* $T_a > T_b$ $GDD_i = GDD_{i-1}$ $+ T_a - T_b$ *else* $GDD_i = GDD_{i-1}$	*if* $T_a > T_b$ $GDD_i = GDD_{i-1}$ $+ (T_a - T_b)*P$ *else* $GDD_i = GDD_{i-1}$	*if* $T_1 < T_a < T_2$ $GDD_i = GDD_{i-1}$ $+ T_a$ *else* $GDD_i = GDD_{i-1}$	*if* $T_1 < T_a < T_2$ $GDD_i = GDD_{i-1} + T_a*P$ *else* $GDD_i = GDD_{i-1}$	*if* $T_1 < T_a < T_2$ $GDD_i = GDD_{i-1} + T_a$ *if* $T_1 > T_a$ $GDD_i = GDD_{i-1} - \lvert T_1 - T_a \rvert$ *if* $T_2 < T_a$ $GDD_i = GDD_{i-1} - \lvert T_2 - T_a \rvert$	*if* $T_1 < T_a < T_2$ $GDD_i = GDD_{i-1} + T_a*P$ *if* $T_1 > T_a$ $GDD_i = GDD_{i-1} - \lvert T_1 - T_a \rvert$ *if* $T_2 < T_a$ $GDD_i = GDD_{i-1} - \lvert T_2 - T_a \rvert$
Parameters	T_b from 0 to 25°C	T_b from 0 to 25°C	$T_1$from -5 to 10°C $T_2$from 10 to 30°C	$T_1$from -5 to 10°C $T_2$from 10 to 30°C	$T_1$from -5 to 10°C $T_2$from 10 to 30°C	$T_1$from -5 to 10°C $T_2$from 10 to 30°C

Comparison of Thermal Indices

For each block and each year, the dates of bloom and veraison have been expressed in each thermal index and normalized by the average date of veraison expressed in the given index and calculated for all the years of the given block. For each block and each thermal index, the Euclidean distances between the dates of respectively bloom and veraison have been calculated two by two and summed squared. The results per vineyard were obtained by summing the corresponding distances of the three blocks. They are noted phenological deviation of the corresponding vineyard.

For each vineyard, the thermal index resulting in the minimum phenological deviation has been selected, apart from calculation artefacts due to too elevated base temperature (Index 1) or too close temperature thresholds (Indices 2 and 3).

In order to better understand the meaning of a degree in the selected thermal indices, the maximum observed deviation of flowering and veraison dates was calculated in civil days *i.e.* day of the year (DOY) and in DOY equivalents of the thermal indices. These equivalents were approximated by dividing the date of flowering or veraison expressed in the given thermal index by the average temperature (and possibly photoperiod) at plus and minus five DOY around the considered phenological stage.

Results and Discussion

Table 3: Minimum phenological deviation and corresponding thermal index for vineyards A, B and C.

	Index 1		Index 2		Index 3	
	1a	1b	2a	2b	3a	3b
Vineyard A	T_b = 4°C **0.9**	T_b = 4°C **1.02**	T_1=10°C T_2=29°C **1,27**	T_1=10°C T_2=29°C **1,28**	T_1=9°C T_2=30°C **1,51**	T_1=10°C T_2=28°C **1,52**
Vineyard B	T_b =0 °C **0.38**	T_b = 0°C **0.36**	T_1=5°C T_2=29°C **0.32**	T_1=5°C T_2=29°C **0.28**	T_1=5°C T_2=29°C **0.32**	T_1=5°C T_2=29°C **0.28**
Vineyard C	T_b =6 °C **2.97**	T_b =5 °C **2.94**	T_1=10°C T_2=28°C **2.52**	T_1=10°C T_2=29°C **2.43**	T_1=10°C T_2=28°C **2.45**	T_1=10°C T_2=28°C **2.37**

For each type of thermal index, in bold type: phenological deviation with corresponding parameters T_b: base temperature, T_1: minimum temperature threshold, T_2: maximum temperature threshold. Surrounded cell: local thermal index selected for the vineyard.

Independently on the thermal index considered in Table 3, the phenological deviation are smaller for Vineyard B than Vineyard A and for Vineyard A than Vineyard C. Part of this statement may be due to the different number of years considered in each data set. The thermal index allowing a minimal deviation of bloom and veraison dates are not the same from one vineyard to another: Index 1a with a base temperature of 4°C is selected for vineyard A, Index 2b with temperature thresholds of 5°C and 29°C is selected for vineyard B and Index 3b with temperature thresholds of 10°C and 28°C is selected for Vineyard C. On the basis of the working hypothesis, this means that the local effect of temperature on grapevine development is different for the three vineyards. The effective growing daily average temperatures seem to be situated above 4°C for Vineyard A and do not seem to present a maximum. The base temperature is lower than those mostly found in the scientific literature (Zapata *et al.,* 2015, 2017). The effective growing daily average temperatures seem to be situated between 5 and 29°C for Vineyard B. The effective growing daily average temperatures seem to be situated between 10 and 28°C and temperatures exceeding these thresholds seem to be detrimental to grapevine development for Vineyard C. Upper thresholds are coherent with optimal growing temperatures around 25°C announced by numerous literature studies (Vasconcelos *et al.,* 2009).

Non-growing events as defined locally for each vineyard, *i.e* daily average temperatures exceeding local base or threshold temperatures, are present in each data set. The selection of thermal indices is therefore not due to a data set effect, for which extreme temperatures would be absent. Instead, variations in plant material (clone and rootstock), environment and cultural practices may explain these differences.

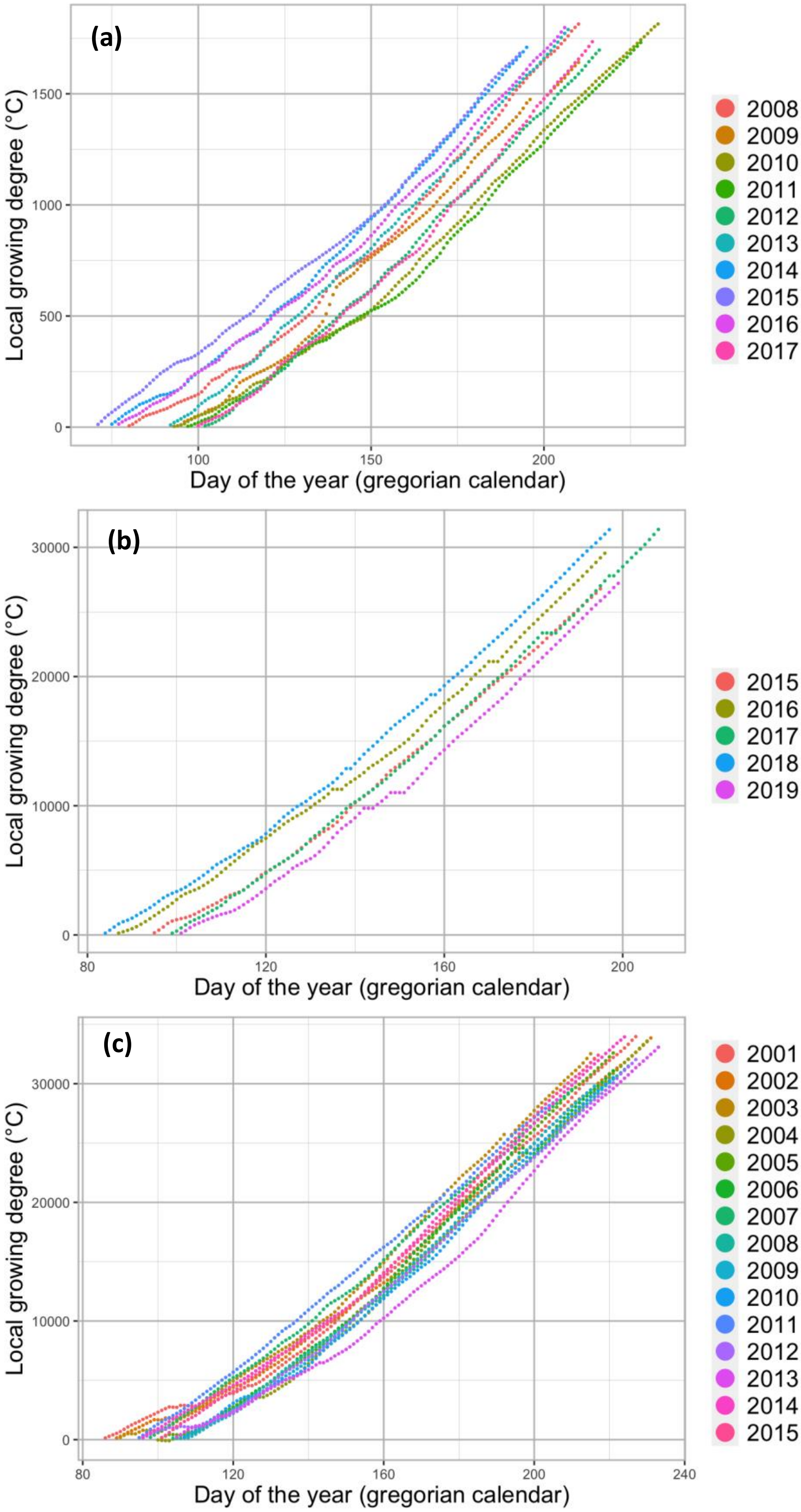

Figure 1: Annual profiles of local thermal indices from bud break to veraison for one block of (a) Vineyard A, (b) Vineyard B, (c) Vineyard C as a function of time (DOY).

Figure 1 shows that the calculated growing degrees have the same unit (°C) but not the same meaning: 1°C in the thermal index of Vineyard A corresponds to less degrees felt in reality than 1°C in the thermal index of

Vineyard C. Moreover, the photoperiod is only used in the computation of the indices of Vineyards B and C. As a result, the scales of growing degree are different between vineyards: from 0 to 1700 °C for Vineyard A and from 0 to 32000°C for Vineyards B and C. The profiles have the same shape, as they all come from a linear computation. However, differences can be observed between the years of each vineyard, in particular with slowing and speeding effects of the effective growing temperature. For example, slowing effects can be observed for 2019 in Figure 1(b) and for 2013 in Figure 1(c). Speeding effects can be observed for 2008 in Figure 1(a). Regarding the years of the same block or the different vineyards for the same year, it should also be noted that profiles do not all start at the same time (depending on the bud break date) and do not all have the same duration. These differences are illustrated by the computation of phenological deviation.

Table 4: For each vineyard, average across the three blocks of the maximum deviation between the dates of flowering and veraison expressed in DOY and in DOY equivalents for the selected thermal index.
In bold: DOY or DOY equivalents in the selected local index. In italics: average across the three blocks of the maximum deviation between the bloom or veraison dates expressed in the local thermal index, average day temperature around bloom or veraison and average photoperiod around bloom or veraison used to compute DOY equivalents.

	Average of the maximum deviation between the bloom dates by block (**DOY**)		Average of the maximum deviation between the veraison by block (**DOY**)	
	Gregorian calendar	Local thermal index	Gregorian calendar	Local thermal index
Vineyard A	**42**	**15** *216.2°C , 18.4°C*	40	**10** *172.8°C , 21.1°C*
Vineyard B	**19**	**3** *889.5°C , 21.1°C , 13.7h*	12	**12** *4015.3°C , 24.5°C , 14.1h*
Vineyard C	**38**	**21** *4149.7°C , 14.6°C , 13.3h*	27	**24** *5456.6°C , 16.8°C , 13.7h*

The average DOY deviation between the dates of bloom and veraison are respectively smaller for all local thermal indices than for the Gregorian calendar (Table 4). According to the working hypothesis, this means that each local thermal index better reflects the physiological processes underlying grapevine phenology in the given vineyard.

The local thermal index allows a reduction of respectively 65% and 75% in the deviation between the dates of flowering and veraison of the blocks of Vineyard A. The local thermal index provides a deviation of three DOY equivalents between the flowering dates of the blocks of Vineyard B. This deviation seems acceptable regarding the operational needs for decision support of cultural practices. However, the respective deviations between the dates of bloom and veraison are only improved by 45% and 15% for the blocks of Vineyard C. Thus, it can be considered that there exists another thermal index that would allow a better expression of the phenology of Vineyard C. In that sense, other thermal indices should be explored in future work. In particular, it can be noticed in Table 4 that the deviation between flowering dates are more improved by the local thermal index than the deviation between veraison dates for Vineyards B and C. This suggests that climate-related physiological processes may not be the same for the two phenological stages. It might therefore be relevant to test non-linear thermal indices to constitute a common timeline for the whole season of grapevine development (Sadras and Moran, 2013; Parker *et al.,* 2020). In addition, the computation of local indices on the basis of daily average temperatures implies that the physiological processes to be illustrated are sensitive to relatively long thermal episodes. However, it has been shown that short exposures to intense temperatures can have an impact on grapevine development (Gouot *et al.,* 2019). It could therefore be useful to include daily maximum and minimum temperatures or even hourly temperatures in the computation of new indices in order to better represent the thermal conditions of the day (Rienth *et al.,* 2014). In this study, the photoperiod was used as a means of reporting the duration of exposure to effective temperatures for grapevine development. This seems indeed to improve the deviations between the bloom and veraison dates for almost all indices and all vineyards (*cf.* Table 1). However, temperature and light are considered as presenting combined effects. When data is available in the field, it could therefore also be interesting to include radiation in the computation of local indices (Prats-Llinàs *et al.,* 2020).

In this study, the working hypothesis was to consider that the collected dates of phenological stages faithfully represent a locally identical process from one year to another if expressed in a relevant local climatic index. However, not all plants in the same block reach these phenological stages completely synchronously. This makes it difficult to assess precisely when 50% of the block has actually reached a given stage. The deviations observed between the bloom and veraison dates necessarily contain noise related to this difficulty. Moreover, it should be noted that, in this study as it is always the case operationally in the field, weather data is recorded using a single station for the three blocks of each vineyard. It is therefore not exactly representative of the meso- and microclimatic conditions actually experienced by the plants, according to environmental factors such as topography, elevation, exposition *etc.* This may also explain part of the irreducible noise that exists when comparing the dates of the phenological stages expressed in climatic indices.

Finally, for operational reasons, this study only considers the beginning of the grapevine growing period, by stopping at veraison. It would obviously be beneficial to complete this work by considering other phenological stages and see if the selected thermal indices are still the same.

Conclusion

This study showed that local *i.e.* site-specific thermal indices can better show the consistency of the dates of bloom and veraison achievement between the different seasons experienced by the blocks of the same vineyard. By using these indices as a timeline to express the timing of any other explanatory variables consistently with grapevine phenology, a further objective of this work is to better understand the influence of environmental factors such as climate or cultural practices on grapevine development and yield. In addition, by focusing on operational data from commercial vineyards, this work opens up opportunities for site-specific local calibration of thermal indices for vineyard management purposes.

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